Physical modelling in *Géotechnique*

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ABSTRACT

This paper reviews the major contributions to *Géotechnique* that relate to physical modelling, which include developments in modelling technology, important experimental observations, and the resulting advances in geotechnical engineering. An increasing proportion of the papers published by this journal involve to physical modelling, conducted either at '1-g' or in a geotechnical centrifuge. Over the 60 years since *Géotechnique* was first published, experimental techniques have advanced significantly, improving the realism of small scale simulations, and raising the quality and detail of the measurements that can be made. These techniques are reviewed, and some of the consequent advances in relation to foundations, tunnels, retaining walls and slopes are highlighted, as reported in the pages of *Géotechnique*.

INTRODUCTION

Since the birth of *Géotechnique*, physical modelling has matured as an experimental technique relevant to geotechnical engineering. The key milestones of this development are described in the pages of *Géotechnique*, which has been chosen by many involved in physical modelling as the repository for their best work. In this paper, the major contributions to the development of geotechnical physical modelling are highlighted and some of the resulting advances in the theory and practice of geotechnical engineering are described.

A total of ~200 papers, representing ~6% of the *Géotechnique* archive, are primarily concerned with physical modelling, and many others make reference to this body of work. However, during the first 20 years of *Géotechnique*, from 1948 – 1968, only ~10 papers described physical modelling; one every second year, representing 1-2% of the journal. Most of these early contributions describe model tests conducted in large tanks – generally of sand – which aimed to establish the forces on retaining walls and piles. These models were not intended to replicate any particular field scale equivalent, but were aimed at understanding generic modes of behaviour.

In 1970, the Rankine lecture delivered by Roscoe (1970) included a description of the 5 m radius geotechnical centrifuge which had recently been commissioned in Cambridge, UK – a machine described as "*terrifying*" by de Josselin de Jong, in his vote of thanks. Roscoe showed how the progressive failure of a kaolin slope could be simulated in the centrifuge. Later that year Lyndon & Schofield (1970) published the results from a similar experiment conducted using the geotechnical centrifuge at UMIST in Manchester, using London Clay. Their post-failure cross-sectional view – drawn with the dimensions multiplied up to the field scale equivalent – is at first sight indistinguishable from the many cross-sections of field scale slope failures found in the early volumes of this journal (Figure 1). The challenge set out by Roscoe was that "*the only satisfactory way of truly modelling to scale a prototype problem, in which the self-weight of the soil is significant, is to use a centrifuge*".

Over the following 40 years around 90 papers on centrifuge modelling have been published in *Géotechnique* – 23 in the past 5 years. Many early developments in centrifuge techniques took place in the UK, in Cambridge and Manchester. *Géotechnique* contains many of the key publications emerging from this work, together with numerous contributions from the international centrifuge modelling community.

However, Roscoe's intermediate clause – "*in which the self-weight of the soil is significant*" – should not be forgotten. Significant contributions to *Géotechnique* also include physical modelling of geo-environmental processes and small *in situ* testing tools, which can be simulated in conditions which replicate field scale behaviour without the inconvenience of an inhospitable centrifuge environment. Furthermore, as described later, many valuable aspects of geotechnical behaviour have been elucidated through small scale model tests conducted at '1-g' – taking advantage of the easier control of events compared to the centrifuge.

Two key developments have advanced the art of geotechnical physical modelling over the past 50 years. The development of the centrifuge in the 1970s allowed the realism of physical modelling to be enhanced, through the correct modelling of self-weight stresses. The subsequent development of miniaturised electronics and micro-computers has led to enhanced methods of data acquisition, control, and image analysis. The refinement of these techniques continues to yield dramatic improvements in the utility of physical modelling. More realistic simulations can be conducted, and more detailed observations can be gathered.

PHYSICAL MODELLING TECHNIQUES

Geotechnical centrifuge development

Approximately half of the ~200 physical modelling contributions to *Géotechnique* make use of a centrifuge in order to ensure that the stress levels in the model are comparable to field scale conditions. The majority of these papers describe research conducted in Cambridge or Manchester, in the groups led by Professor Andrew Schofield and Professor Peter Rowe respectively. Schofield and Rowe pioneered the use of the geotechnical centrifuge in Europe, in parallel with developments in Japan and following earlier work in the USSR, which was at that time unknown in the west. The idea of using a centrifuge to correctly model civil engineering structures in which self-weight forces are significant can be traced back to the French engineer, Édouard Phillips, in the 19th century, as described in *Géotechnique* by Craig (1989).

The earliest mention of centrifuge modelling in the pages of *Géotechnique* is the final section of Roscoe's Rankine lecture, delivered in 1970. Despite leading a research group focussed on the development of theoretical models for soil behaviour, he argued boldly that "*with the centrifuge it is possible to obtain answers immediately to full-scale problems without having to appeal to, or wait for the development of, any theory*". In a letter to Géotechnqiue, Golder (1971) relates a more light-hearted attempt to test soil using centrifugal force, which was conducted on the lawn outside the UK Building Research Establishment in 1936.

Rowe's Rankine lecture, given in 1972, was concerned with the identification of soil fabric during site investigations, but concluded with a description of the second geotechnical centrifuge built in Manchester – at the (then) Victoria University of Manchester (Rowe 1972). Unlike most physical modelling, Rowe's work relating to site-specific situations frequently involved using intact samples of natural soil, which were built into models placed within the centrifuge. This approach followed rationally from his conclusion that strength and consolidation testing of natural soil elements in the laboratory should be conducted in cells sufficiently large to accommodate representative amounts of the natural fabric – leading to the consolidation device now known as the 'Rowe' cell. Applying this logic to the centrifuge and his particular interest in earth embankment dams led him to design a machine sufficiently large to accommodate soil models which are 1 m × 2 m in plan.

Some of Rowe's most significant centrifuge work, conducted with Craig, contributed to the development of the large gravity platforms deployed in the North Sea in the 1970s and the Oosterschelde storm surge barrier. These studies influenced the final form of these structures, and provided the necessary performance data to support the design (Craig 2002, Smith 1997).

Ten years after Roscoe's Rankine lecture, his successor, Schofield, delivered the Rankine lecture (Schofield 1980), focussing on centrifuge operations in Cambridge. Twenty-six years later, in 2006, Professor Robert Mair – Schofield's successor – delivered the Rankine lecture (Mair 2008), and also described extensive centrifuge modelling studies conducted in Cambridge. Working alongside Schofield and later Mair, Professor Malcolm Bolton, another strong proponent of centrifuge modelling, has made more than 40 contributions to *Géotechnique*, many of which are concerned with centrifuge modelling.

The research conducted by the groups in Cambridge and Manchester, and the resulting sequence of Rankine lectures, provide the backbone of the *Géotechnique* archive of centrifuge modelling research, but many seminal contributions come from elsewhere. During the past 10 years, *Géotechnique* has featured centrifuge modelling articles from research groups in Japan, Singapore, France, Germany, the USA and Australia in addition to the UK.

Modern experimental methods

Modern geotechnical physical modelling, in parallel with other branches of experimental mechanics, has benefited from digital and robotic technology, which has allowed improved control and monitoring. In early physical model tests, such as the classic experiments on piles and walls by Marsland (1953), Whitaker (1957) and Hanna (1963), external loads were applied by modified strength testing machines and ground movements were monitored by dial gauges – or in Marsland's case by eye through a microscope. In early centrifuge tests, load was imposed by self-weight alone, due to the inability to provide control within the centrifuge environment.

Recent editions of *Géotechnique* include examples of the more sophisticated experimental methods which represent the evolving state-of-the-art. Many ingenious devices have been developed to replicate construction activity at small scale, often in a centrifuge. New techniques have been developed to simulate excavation and backfilling in-flight. These include the simple approach of draining heavy fluid to simulate the reduction in stress during excavation or tunnelling (Davis et al. 1980, Bolton & Powrie 1988), which has been augmented by techniques for in-flight 'concreting' of diaphragm walls (Powrie & Kantartzi 1996), insertion of props (Richards & Powrie 1998, Figure 2a), loading of adjacent piles (Choy et al. 2007), and deterioration of sewer linings (Spasojevic et al. 2007).

To install foundations in a realistic manner, miniaturised systems for hammer-driving (De Nicola & Randolph 1997) and suction pumping (Gaudin et al. 2006, Chen & Randolph 2007, Figures 2c, 2d) have been devised. Model test beds have been improved with dynamic compaction (Merrifield & Davies 2000), miniature vertical drains (Hird & Moseley 2000) and stone columns (Muir Wood et al. 2000, Al-Khafaji & Craig 2000). Robots have been developed to construct sand compaction piles (Lee et al. 2004) and conduct deep mixing (Lee et al. 2006) in the centrifuge.

Earthquake loading has been simulated on shaking tables, although this research is poorly represented in *Géotechnique*, featuring only as a small section of Newmark's (1965) Rankine lecture. Earthquakes have been modelled in the centrifuge (Scott 1987, Lee & Schofield 1988, Hushmand et al. 1988, Kutter & James 1989) using special containers developed to reduce boundary effects (Zeng & Schofield 1996, Teymur & Madabhushi 2003) and artificial pore fluids to ensure correct scaling of inertia and consolidation (DeWoolkar et al. 2007). Liquefaction from wave loading has also been simulated (Sassa & Sekiguchi 1999).

Servo-controlled actuators have been developed to allow arbitrary sequences of load and displacement to be imposed on model structures and foundations. Martin & Houlsby (2000) describe a foundation loading system with full control of three axes – vertical, horizontal and rotational. Bienen et al. (2006) describe a miniature Stewart platform (Stewart 1965) which provides control of all six degrees of freedom – three translational and three rotational (Figure 2b).

To allow proper back-analysis of a physical modelling event, it is necessary to conduct the miniature equivalent to a ground investigation in order to characterise the test bed. For this purpose, miniature vane shear and cone penetration test devices have been devised, and adapted for in-flight use in the centrifuge (Davies & Parry, 1982, Bolton et al. 1999). These devices have been used to illustrate the repeatability that can be achieved, as evidenced through CPT tip resistance profiles recorded in the same type of sand tested at 6 different European centrifuge laboratories: a variation of 10% was found (Bolton et al. 1999). In a reversal of the centrifuge testing philosophy of miniaturising reality, an enlarged version of the original T-bar penetrometer, which was first developed for use in the centrifuge (e.g. Stewart et al. 1994, Horikoshi & Randolph 1996), has become popular in the field as an *in situ* test for characterising soft sediments (Randolph et al. 1998, Kolk & Wegerif 2005).

To measure displacements within an exposed plane of a soil model, Butterfield et al. (1970) and Andrawes & Butterfield (1973) described a technique based on stereo photogrammetry, which provided remarkable accuracy. By manually measuring particle movements, as seen in stereo pair photographs, displacements as small as a fraction of a grain size could be detected over a ~0.5m field of view. The recent introduction of digital technology has removed the need for painstaking manual measurements, and pre-failure deformations can now be detected using digital imaging combined with particle image velocimetry (PIV) and close range photogrammetry (White et al. 2003). Photographic techniques are limited to the observation of external surfaces, but Borsic et al. (2005) describe how electrical impedance tomography can reveal the internal density distribution of a soil model. Miniature transducers have been developed to measure stress (Garnier et al. 1999) and pore pressure (Take & Bolton 2003) within soil masses, and earth pressures on foundations and piles (Klotz & Coop 2001, White & Lehane 2004, Chen & Randolph 2007 (Figure 2d), Choy et al. 2007).

Each of the following sections focuses on a particular type of geotechnical construction. Some of the most significant developments that have emerged from physical modelling are highlighted.

SHALLOW FOUNDATIONS

The load-displacement response of a shallow foundation remains a significant area of geotechnical engineering research, and is the subject of more than 20 papers in *Géotechnique* during the past five years. Early work by Meyerhof (1951), Hanna (1963) and De Beer (1963, 1970) described extensive model tests and limit equilibrium solutions, which established the general bearing capacity expressions that feature in every undergraduate text book. Meyerhof, De Beer and Hanna all recognised the difficulty of selecting an appropriate friction angle to use in the bearing capacity equation. This difficulty arises because peak friction angle varies with stress level, and a range of stress levels exist within the failing soil beneath a footing. Bjerrum, in a special lecture that was never delivered due to his sudden death, but which was published in *Géotechnique* in 1973, highlighted the implications of this uncertainty in relation to the design of the first concrete gravity structure installed in the North Sea. "A *variation in friction angle of only 2° may result in a variation in the value of* N_γ *of 50%. Most of the* [existing expressions for N_γ] *are derived in a semi-empirical way, being based partly on the results of loading tests. The loading tests are, however, in most cases carried out with model footings of very small size, the dimensions generally being of the order of inches, or at the most one or two feet. Extrapolation of the results to the structures in the North Sea having dimensions of about 330 ft (100 m) therefore requires careful consideration of the scale effect*" (Bjerrum 1973).

With the advent of centrifuge modelling in the early 1970s, it became possible to simulate large-scale footings in controlled and repeatable soil conditions, eliminating the need for extrapolation. The classic parametric studies by Ovesen (1975) and Kimura et al. (1985) clarified the variation of N_γ with footing size, whilst confirming, through 'modelling of models' that small centrifuge tests were free from unwanted errors associated with grain size (Steenfelt 2006). Ovesen's classic study draws on his own tests conducted in Florida, combined with data gathered by Mikasa & Takada (1973) in Japan. In these tests, the observed unit bearing capacity was consistent for a given prototype (i.e. field scale) footing size, regardless of whether the model was 10 mm or 30 mm in diameter – representing successful modelling of models. In contrast, as the prototype footing diameter increased, the unit bearing capacity decreased. Ovesen's study involved small models and relatively low acceleration levels. During the same period, Rowe & Craig (1979), working in Manchester, were simulating gravity platforms up to 100 m in diameter, to support the early oil and gas developments in the North Sea.

Bjerrum's concern with establishing a value for the vertical bearing capacity factor, N_γ stemmed not from any concern that the 100 m diameter Ekofisk tank would sink vertically, but because the resistance to inclined loading (resulting from wave action) was assessed by applying a reduction factor to the capacity under purely vertical load.

An alternative approach to describe the capacity of a foundation under combined loading is to consider the capacity in terms of an envelope in vertical, horizontal and moment (V-H-M) load space. The first mention of this approach in *Géotechnique* is on the second page of Roscoe's Rankine lecture, in which he relates how Sir John Baker asked him to design the foundations of a portal frame, to support the V, H and M loads given to him by the structural engineer. Roscoe & Schofield (1956) plotted the capacity of the resulting foundations as an envelope in combined load space. However, the pages of *Géotechnique* portrayed combined loading in terms of inclination and eccentricity factors for a further 35 years, until Nova & Montrasio (1991) proposed a return to the yield envelope approach, which they coupled with a work-hardening plasticity theory to describe the general footing response. The theory was compared with results from a programme of model tests and was able to calculate the footing displacements at yield, and subsequent hardening or softening of the footing response. This form of plasticity model "*treats in a unifying conceptual framework both displacements under working loads and failure conditions*" (Nova & Montrasio 1991).

Based on these and other model tests, Butterfield & Gottardi (1994) suggested that the failure surface approach "*might replace, in a simple and more useful form, the plethora of load inclination and eccentricity factors currently used to predict such failure loads*". Further papers in *Géotechnique* describe the highly sophisticated physical model tests which have underpinned the development and calibration of these plasticity 'macro-element' models for foundation behaviour (Montrasio & Nova 1997, Gottardi et al. 1999, Martin & Houlsby 2000 (Figure 3a), Byrne & Houlsby 2001, Cassidy et al. 2004). Centrifuge model tests validated a more simple approach for incorporating the benefit of rotational fixity into the analysis of the 'spudcan' foundations of jack-up drilling rigs (Dean et al. 1998). Centrifuge modelling studies have also provided guidance on other aspects of the behaviour of spudcan foundations, including punch through failure in sand-over-clay conditions (Craig & Chua 1990), bearing capacity and soil backflow during deep penetration (Hossain et al. 2005, Figure 3b) and the increased extraction resistance due to consolidation during operation (Purwana et al. 2005).

These physical model tests have validated many aspects of the analysis techniques that are used in practice and are found in international design codes for offshore structures (SNAME 2002, ISO 2008). For onshore design, centrifuge model tests have also been used to validate simplified approaches for calculating foundation settlement, accounting for soil non-linearity (Atkinson 2000).

TUNNELLING

The stability of tunnel headings and the ground movements associated with tunnel construction have been widely investigated through physical model tests. A classic series of model tests accompanied by limit plasticity analysis led to the development of calculation methods for the collapse of tunnels in sand (Atkinson 1975, Atkinson & Potts 1977) and in clay (Davis et al. 1980). These tests, and other more recent studies, have been used to calibrate simplified methods for predicting tunnelling-induced ground movements, which closely match recent field measurements (Mair et al. 1993, Loganathan et al. 2000 (Figure 4), Osman et al. 2006a). The early tests have been revisited recently to calibrate simplified approaches to link tunnel support pressure to surface settlement (Osman et al. 2006b). Physical modelling is particularly valuable to the understanding of tunnel behaviour because numerical modelling is unable to match observed settlement troughs even when using a highly sophisticated constitutive model and including three-dimensional effects and anisotropy (Franzius et al. 2005).

RETAINING WALLS

Physical model tests published in *Géotechnique* have been used to assess the validity of theoretical analyses for the limiting pressures on retaining walls (e.g. Rowe & Peaker, 1965 (Figure 5a); James & Bransby 1970; Powrie 1996; Bica & Clayton 1999). These tests have also been used to identify the resulting soil deformation mechanisms and therefore the nearby settlement and pre-failure wall movements (Bransby & Milligan, 1975; Milligan & Bransby, 1976; Bolton & Powrie 1988). These observations inspired simple kinematic mechanisms for the prediction of wall and ground movement during excavation. These mechanisms provide a link between soil strain and wall movement, at least for a relatively rigid wall. Mechanisms of this kind allow an assumed soil stress-strain response to be used to select a wall embedment that is sufficient to limit ground movements to a specified serviceability limit (Bolton & Powrie 1988) and can be found in modern text books (Wood 2004, Powrie 2004).

In their centrifuge tests of unpropped diaphragm walls in stiff clay, Bolton & Powrie (1987) observed the formation of a flooded tension crack on the retained side of the wall (Figure 5b). They argued that designers "*should always be aware of this possibility: stability under these* *conditions might be viewed as a minimum requirement for any wall*", although if the retained area is paved over or built on, tension cracks may be prevented. However, cantilever flood defence walls, such as those which failed when Hurricane Katrina struck New Orleans in 2005, are vulnerable to this mechanism. During the subsequent investigation, physical model tests were conducted using the US Army geotechnical centrifuge to identify the modes of failure. It was established that "*a key factor in the failure was the formation of a gap between the wall and the levee fill on the canal side of the wall, allowing water pressure to act on the wall below the surface of the levee*" (IPET 2007, Steedman 2006). This possibility was not considered during the design of the wall. An additional destabilising mechanism identified by these tests was the creation of high uplift pressures in the sand beneath the embankment by the water flowing down the gap. This same uplift mechanism has been observed in centrifuge model tests, as reported in two *Géotechnique* papers that have identical titles (and the same last author) (Hird et al. 1978, Padfield & Schofield, 1983).

SLOPES

In his Rankine lecture on slope behaviour, Leroueil (2001) described the Selborne cut slope experiment (Cooper et al. 1998) as "*the first time that the development of progressive failure up to generalised failure has been observed*". This comment is only strictly true if referring to field observations. Quantitative measurements of progressive slope failure feature in *Géotechnique* as early as Roscoe's Rankine lecture. His study – the first centrifuge modelling published in *Géotechnique* – includes results from early tests which "*clearly show that the rupture develops progressively upwards from the toe*" (Roscoe 1970). Tension cracking at the surface followed, matching the mechanism observed at Selborne. Subsequent papers describe similar observations, enjoying the advantage over field-scale studies of a full view of the slope cross-section through a window in the model container (Lyndon & Schofield 1970, Endicott 1974). The analysis by Smith & Hobbs (1974) of many centrifuge slope tests conducted in Manchester is the first comparison between finite element and centrifuge modelling to appear in *Géotechnique*, and these authors highlighted the complementary roles of the two modelling techniques, accompanied by field evidence.

These early slope tests were very simple, with failure being initiated by the self-weight of the slope and equilibration of pore pressures. Real slopes are subject to seasonal variations in the hydraulic boundary condition at the free surface, which can drive progressive failure. Take &

Bolton (2004, 2008) (see also Take 2003) revisited the issue of progressive failure that was first tackled in the centrifuge by Roscoe. They subjected their slopes to successive wet and dry seasons within a humidity-controlled chamber equipped with a rainfall simulator (Figure 6). Meanwhile, the patterns of movement within the slope cross-section were tracked to micron-level accuracy using image analysis (White et al. 2003) and the pore pressure response within the slope was measured using miniature tensiometers (Take & Bolton 2003). In these tests, the stress history of the soil, the geometry of the slope, and the imposed changes in humidity, temperature and rainfall were all known and controlled, and the resulting pore pressure and the detailed ground movements were continuously monitored. These tests demonstrated the important role that seasonal cycles of pore pressure have in the progressive degradation of a slope.

CONCLUDING REMARKS

The sophistication of modern physical modelling is epitomised by the study described in the previous paragraph. In many respects, the information available from this centrifuge model is more complete than can ever be gathered in a field test. Other recent papers in *Géotechnique* describe similarly advanced physical modelling studies.

This level of sophistication means that modern physical modelling experiments should be regarded as case studies of comparable value to those undertaken in the field. Field studies have the important benefit of incorporating natural soil properties and variability, whereas physical modelling allows better control of events and ground conditions, and provides more detailed measurements of the resulting behaviour. Unlike a field trial, an experiment can be quickly repeated at will with controlled changes to the soil and boundary conditions. The more controlled conditions in a physical model test compared to the field provide a better basis for establishing the validity of theoretical and numerical analyses.

Many of the model test observations and events described in this paper lie beyond current constitutive and numerical modelling capabilities. Physical model testing in its various forms is therefore to be regarded as a powerful tool that is complementary to numerical modelling and field investigations. Each has a distinct role within the research and practice of geotechnical engineering.

Géotechnique has published many of the key papers that document the evolution of physical modelling over the past 60 years. These papers have revealed a variety of important geotechnical phenomena, and have validated analyses that underpin many aspects of geotechnical practice. As modelling techniques advance, the sophistication of physical models, and the detail of the resulting measurements, will continue to increase. The best of this work will appear in the pages of *Géotechnique*, and should be keenly anticipated.

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FIGURES

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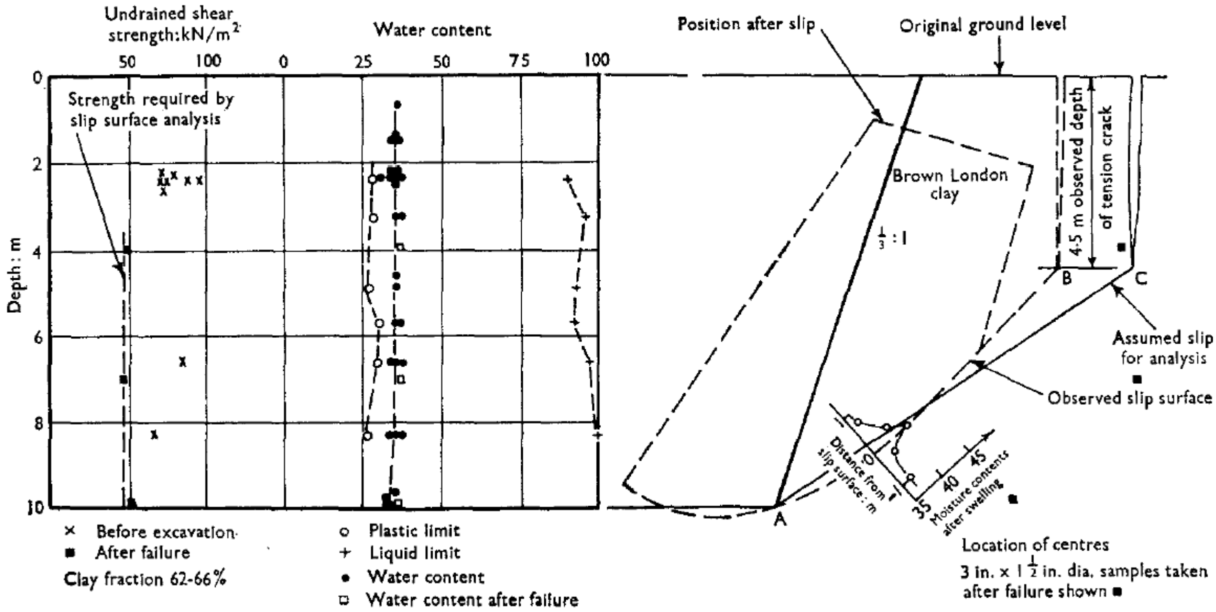
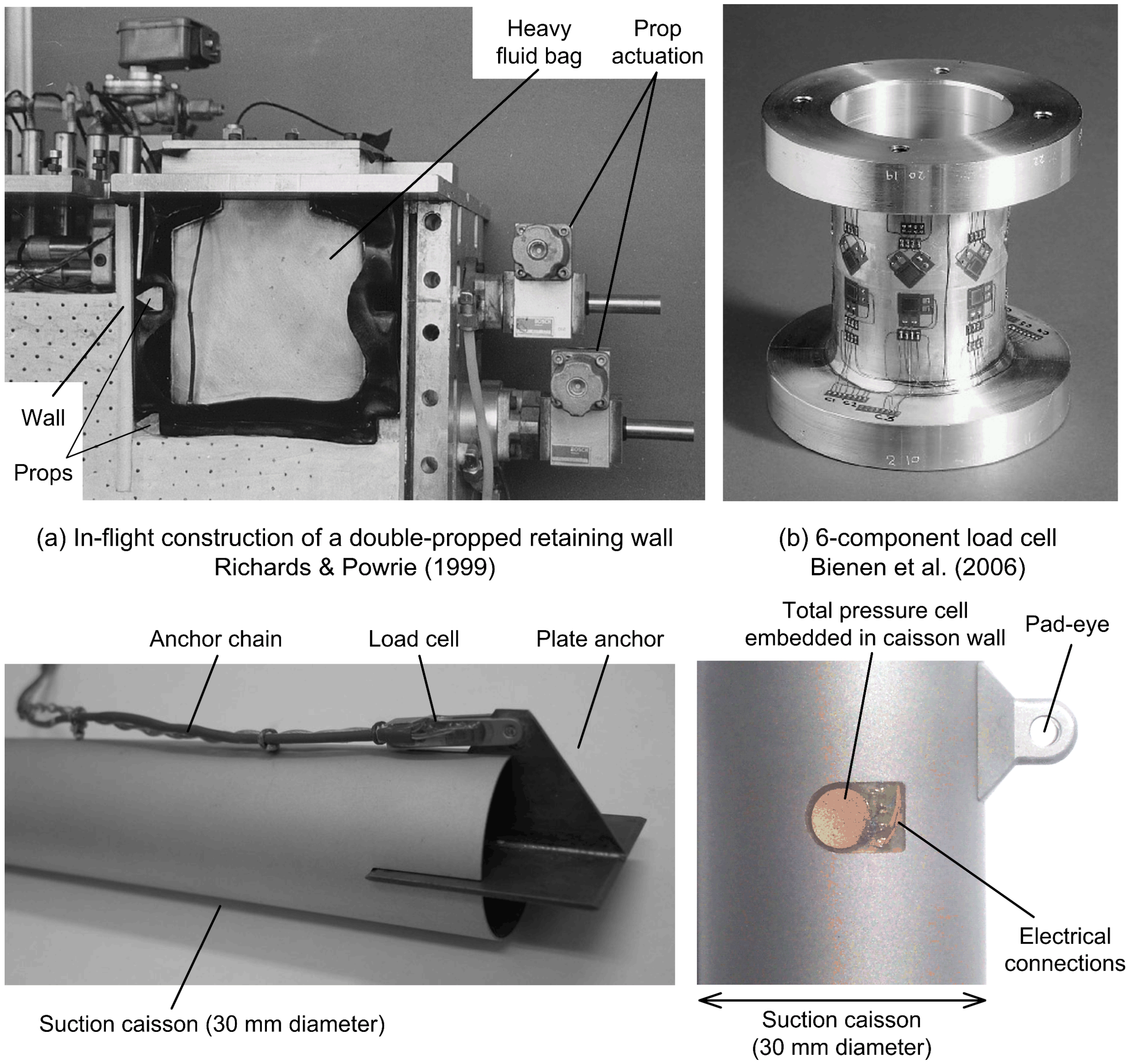


Figure 1. Early physical modelling of slopes: Lyndon & Schofield (1970)



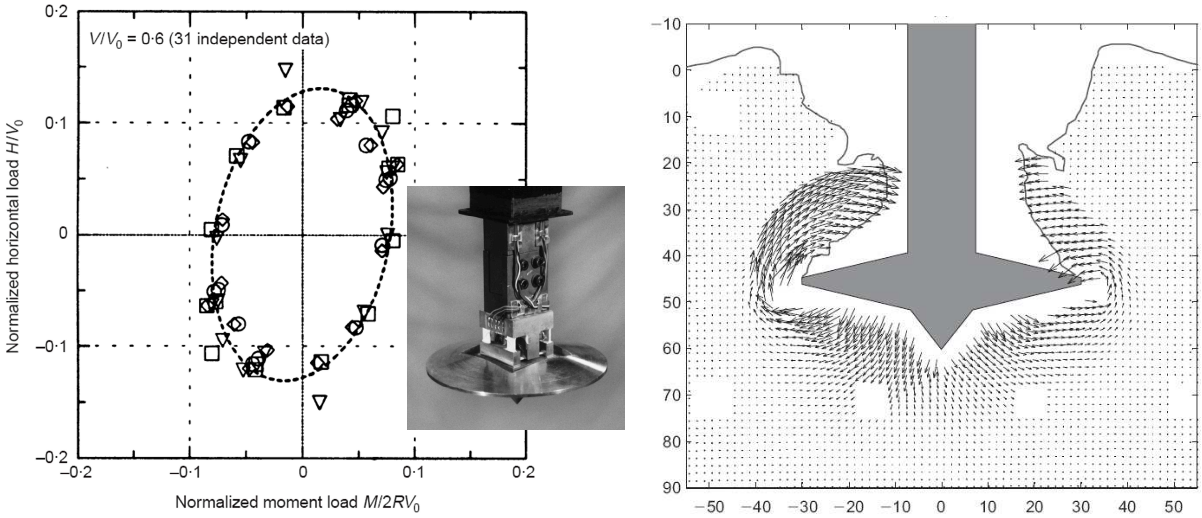
(a) In-flight construction of a double-propped retaining wall
Richards & Powrie (1999)

(b) 6-component load cell
Bienen et al. (2006)

(c) Suction-embedded plate anchor
Gaudin et al. (2006)

(d) Instrumented suction caisson
Chen & Randolph (2007)

Figure 2. Examples of modern physical modelling technology



(a) Capacity under combined loading
Martin & Houlsby (2000)

(b) Backflow during vertical penetration
Hossain et al. (2005)

Figure 3. Spudcan foundations

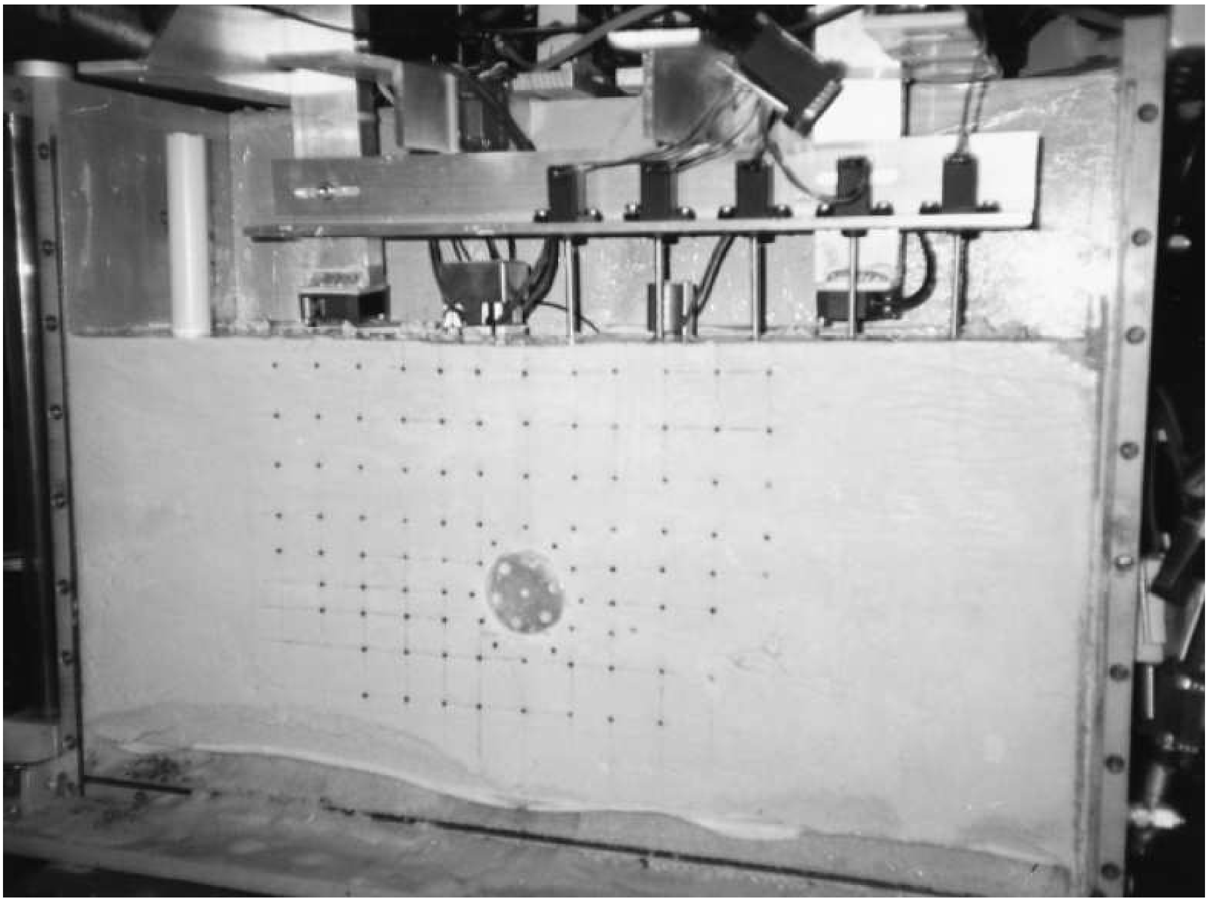
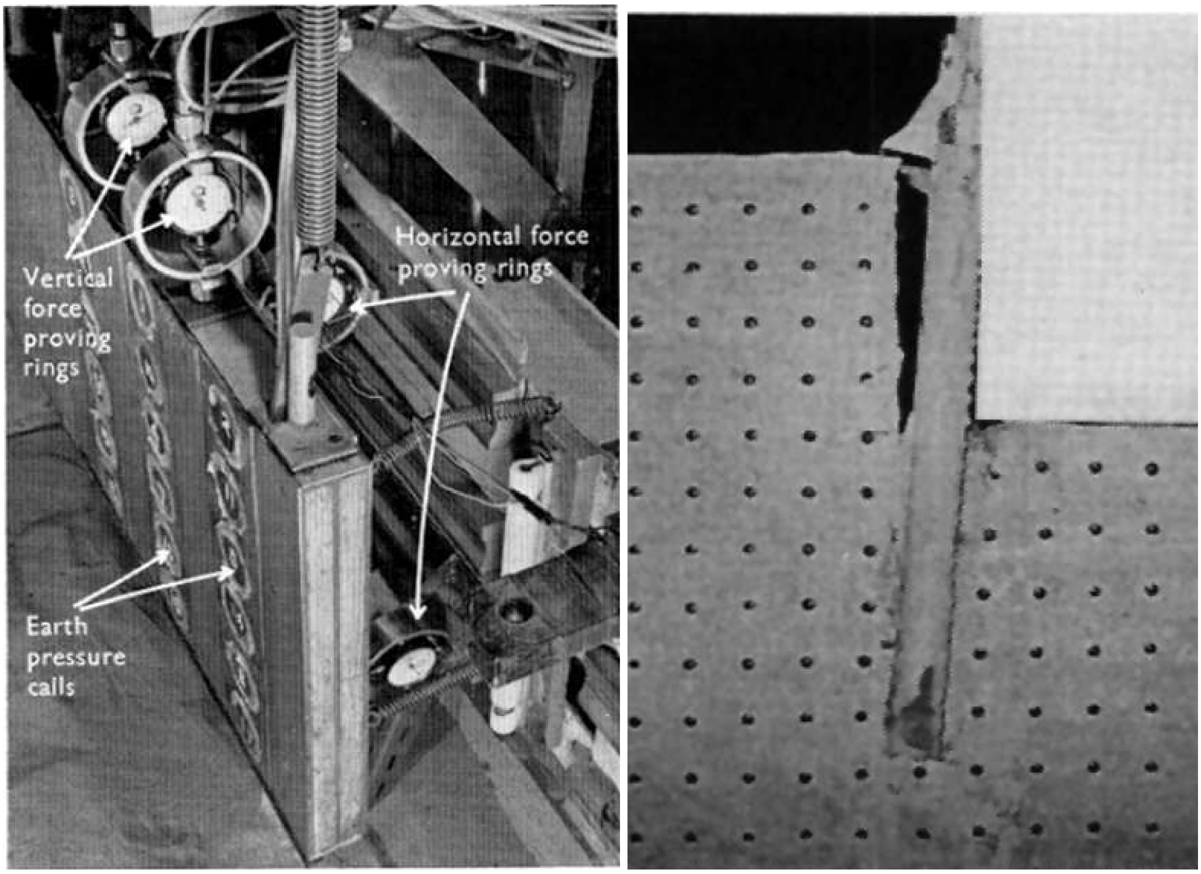


Figure 4. Tunnelling-induced ground and pile deformations (Loganathan et al. 2000)



(a) Early studies of earth pressure
Rowe & Peaker (1965)

(b) Diaphragm wall failure due to tension crack
Bolton & Powrie (1987)

Figure 5. Retaining walls

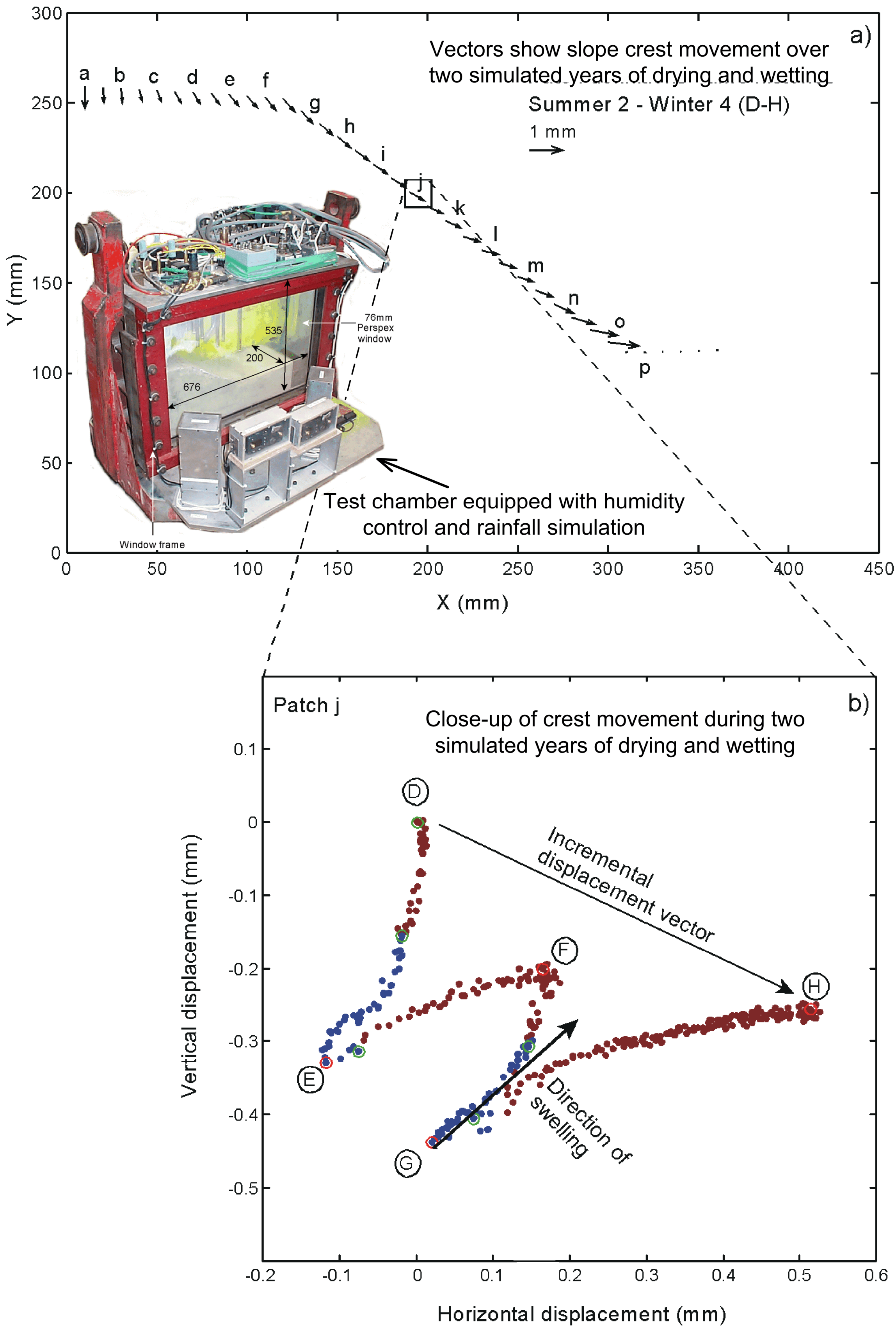


Figure 6. Recent centrifuge modelling of slopes (Take & Bolton 2008)